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(EFFECT OF MOLD-STEEL INTERFACE REACTIONS
ON CASTING SURFACE AND PROPERTIES

FINAL REPORT

July 1, 1963-January 31, 1968

by

Charles E. Bates
Rodney L. Naro
John F. Wallace

January, 1968

Department of Metallurgy
Case Western Reserve University
University Circle
Cleveland, Ohio 44106

Contract No. DA-33-019-AMC-270 (Z)

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ABSTRACT

This project investigated the problem of thermal and mechanical stability of mold materials for high strength steel castings of the 4330 type. The ability of various combinations of rammed refractory aggregates and binders to provide close dimensional control in steel castings was investigated. The aggregates studied included mullite, zircon, silica sand, fused silica, olivine and calcined alumina. These were bonded with western bentonite and sodium silicate. Close dimensional control was obtained with all aggregates bonded with sodium silicate and with the zircon and mullite aggregate bonded with western bentonite. A means of measuring the tensile strength of molding materials at elevated temperatures was developed and the results of this test permit qualitative evaluation of the ability of a mold material to maintain casting dimensions.

The effect of various refractories and different mold coatings on the surface roughness on cast steel and on the impact resistance as measured in reverse bending was also studied. The effects of rammed aggregate of silica, chromite and zircon sands on the surface quality and fatigue behavior were studied. The green silica sand molds were coated with a variety of washes to determine the effect of these coatings of both surface roughness and fatigue behavior. All fatigue specimens were heat treated to approximately 185,000 psi tensile strength.

Test specimens made in both hexachlorobenzene coated silica sand molds and zircon sand produced equivalent results in improving the surface finish of experimental test castings. Bending fatigue test results showed that hexachlorobenzene coated and uncoated zircon provided the greatest overall improvement in fatigue life and endurance limit. Completely machined bending fatigue specimens result in only slight improvements in fatigue compared to sand blasted hexachlorobenzene and zircon specimens with the original cast surfaces. Shot peening these specimens also produced substantial gains in fatigue strength, compared to machined specimens. The fatigue failures were initiated at cope surfaces with greater frequency than drag surfaces.

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INTRODUCTION

Since molding materials are of primary importance in determining the surface quality and dimensional accuracy of steel castings, these require careful consideration by steel founders. A molding material should have the following characteristics to produce high quality castings:

- 1) capability of receiving molten steel without eroding;
- 2) freedom from chemical reaction with the molten or solidifying steel;
- 3) sufficient high temperature strength and a low coefficient of thermal expansion in order to control the dimensions of the castings to close limits.

Molds are composed of an aggregate or inert refractory material and a binder for this aggregate. Both of these components serve an important role in the production of high quality castings. Several criteria must be considered for an aggregate including: melting point, availability in the proper grain fineness range and satisfactory thermal expansion characteristics. This latter factor requires both a low coefficient of thermal expansion and a smooth thermal expansion curve that is free from crystal inversions. The inversions that occur when heating ordinary silica molding materials coupled with its large coefficient of thermal expansion have led to many of the problems associated with the use of this aggregate.

The binder employed in the aggregate-binder mixture is also a very important consideration. Many casting defects can be traced to deficiencies of the binder rather than the aggregate. The binder must be capable of holding the aggregate in position during pattern removal, pouring and solidification of the casting. Maintenance of sufficient high temperature strength, prevention of erosion, mold cracking and spalling are all requirements of a good binder.

In order to develop and test aggregate-binder mixtures that will produce high quality dimensionally stable castings, tests that predict the performance of the molding materials are needed. The results of standard tests producing quantitative results are better for the evaluation of mold materials than those obtained by examination of miscellaneous castings. Unfortunately, standard tests that predict the thermal stability of mold materials as the molten metal enters the mold cavity and solidifies are not available.

The reaction of mold refractories with molten steel at the mold-metal interface has also been a serious problem. This interface reaction is the cause of dimensional inaccuracies, surface roughness, sand penetration, and fused sand on steel castings. It has been studied qualitatively by numerous investigators. Consequences of casting surface defects include a general reduction in mechanical properties, particularly fatigue life. Although steel castings are widely employed in fatigue applications, information on their fatigue properties has indicated that the endurance limit in bending fatigue is sharply reduced by the existence of surface roughness and discontinuities. Surface defects also result in an impairment of the machinability of the casting, since portions of the casting are usually machined to adjust their dimensions for service or other applications.

The underlying causes of poor cast surfaces can be separated into two phenomena: 1) mechanical penetration of the molten steel into the molding aggregate, and 2) chemical reactions occurring between the molten steel and the mold wall interface.

Mechanical penetration occurs when the pressure of the molten metal is high enough to force this metal into the interstices of the mold interface. Many investigators have shown that mechanical penetration is enhanced by the following conditions: 1) high pouring temperatures, 2) high ferrostatic pressure, 3) coarse sand grain distributions, and 4) low density molds. Sand grain size and ferrostatic pressure are usually the controlling factors governing mechanical penetration.

The influence of sand grain size on penetrating is well known. The penetrating pressure is inversely proportional to the sand grain size. Molten metals do not wet silica sand; accordingly, calculations of the ferrostatic pressure head to force metal into the sand capillaries show that pouring heads of 30 to 50 inches are required. The majority of all steel castings are poured without excessive ferrostatic pressure, but considerable burn-on still occurs. Clearly, mechanical penetration concepts cannot account for many cases of sand adherence and the subsequent deterioration of surface quality and casting properties.

The nature of the chemical reactions occurring at the mold-metal interface are less clearly understood. The reaction results in the formation of a fused sand layer adjacent to the casting. Burn-on, as this layer is often called, and the resulting surface roughness of the casting has been studied qualitatively by many investigators. Early investigators conducted superficial tests to determine the characteristics of mold-metal interface reactions. Although the tests did not simulate actual foundry

conditions, the reaction produced appeared to be the result of oxidation of the steel and subsequent reactions between the iron oxide so formed and the silica sand to produce iron silicate or fayalite. When reducing atmospheres were used, no interface reactions resulted.

Modifications have been made to the original proposed mechanism to account for the fused sand layer and the resulting poor casting surface finish. When molten steel is poured into a green silica sand mold, iron oxide is formed at the interface due to the oxidizing nature of the mold. This oxide layer can wet the sand and penetrate into it. More recent developments have shown that aside from wetting the sand, the oxide further dissolves SiO_2 and enlarges the voids between the packed sand grains, allowing molten metal to enter these enlarged voids.

By controlling and eliminating the chemical reaction occurring at the mold-metal interface, improvements in cast surface finish can be obtained. Methods by which this may be accomplished are:

- 1) replacement of SiO_2 with another molding aggregate;
- 2) providing a reducing mold atmosphere with a suitable mold coating;
- 3) providing a viscous fluxing liquid film between the solidifying metal and the mold interface.

PROCEDURE AND MATERIALS

Several aspects of the behavior of moldable refractories for steel casting were investigated. These included: the development and conduct of high temperature sand tests; the casting of steel into molds and evaluation of resulting casting quality and the measurement of mold deformation. Numerous aggregate-binder combinations rammed to different densities were studied.

A modified dog-bone type of tensile test was adapted for the elevated temperature test. Specimens of this type were compacted in a standard type fixture and tested in a furnace constructed around the specimen positioned in a tensile testing machine. The furnace utilized tungsten heating elements encased in fused silica with an insulating brick exterior. Specially designed jaws were employed to grip the specimen and thermocouples were employed to record the temperature. Adjustments in the power supplied to the heating elements permitted obtaining the desired temperature.

The materials selected for testing as molding aggregates included silica sand, fused silica, mullite, zircon, olivine and calcined alumina. Castings were produced in molds rammed from each of these materials and examined for dimensional stability, chemical reaction with the molding material, sand expansion defects and general surface finish. Each of the refractory materials listed above was bonded green with western bentonite, cereal and water. Sodium silicate, set with both CO₂ and silicon metal fines, was also employed as the binder for some of the aggregate materials. All castings produced were in the shape of a scab block developed by the Steel Founders' Society of America with a slight modification of the gating system. Molds were rammed according to a standard procedure that consisted of both jolting and hand ramming the drag and hand ramming the cope.

Molds were poured with a low alloy, aluminum deoxidized steel directly from a basic-lined high frequency induction melting furnace. A standard pouring temperature of 2900°F (1593°C), as determined by an immersion pyrometer, was employed in all cases. Molds were poured on the same day in which they were rammed. Castings were allowed to cool overnight, shaken out, examined, sand blasted and subjected to a final examination for surface condition and dimensions.

Mold deformation caused by the pressure of the molten steel was measured on a series of green and sodium silicate bonded mold at various distances from the mold-metal interface. A fused silica probe extended from this disc to the outside of the mold where it was attached to a linear transducer. Movements of the disc with the mold wall were transmitted by

the probe to the transducer, converted to an electrical signal, and continuously recorded on a calibrated high speed strip chart recorder. The fused silica disc was maintained at the proper distance from the pattern during mold preparation with an accurately machined spacer. This spacer was removed after sufficient molding material had been packed around the disc to support it.

To permit insertion of the silica probe, a 1/4 inch diameter steel rod was positioned inside the mold during mold preparation with one of its ends touching the quartz disc and the other extending to the inside edge of the molding flask. The steel rod was maintained in the proper position during ramming by two supports resting on the pattern board. After the mold had been prepared and the molding flask stripped, the steel rod was removed. The mold was then jacketed, weighted, and the 6mm-diameter fused silica probe inserted through the jacketed mold into the hole. Using a technique that employed a fused silica disc inserted in the mold and held in place with a silica rod, mold deformation was continuously measured at various locations within green sand molds rammed to densities of 90 and 100 lb/cu ft and in sodium silicate bonded molds rammed to a density of 100 lb/cu ft.

The materials selected for testing as refractory mold aggregates of the surface roughness included fused silica, silica sand, calcined kyanite, mullite, olivine, chromite and zircon sands. All molds were poured with a nominal AISI 8630, aluminum deoxidized steel directly from a 100 pound basic lined high frequency induction furnace. A pouring temperature of 3000°F, measured with an immersion pyrometer, was used for all test castings. Castings produced in molds with various aggregates and coatings were examined for chemical reactions, shakeout behavior and general surface appearance. Individual test bars were cut from the gates and sand blasted lightly. The surface condition of each bar was measured with a profilometer after sand blasting.

The metal used for the fatigue studies of the investigation was AISI 4330 steel. The material was melted and deoxidized in a similar manner as the bars used for surface condition evaluation. The steel from each heat was used to cast plate bending fatigue specimens and standard test coupons from which tensile and R. R. Moore fatigue specimens were machined. Coatings and refractories which produced the superior cast finishes were utilized for the production of bending fatigue specimens. The cast bending fatigue specimens were shaken out and lightly sand blasted to facilitate their removal from the gating system. Fatigue specimens were randomly selected for a visual inspection of the cast surface and measurements of surface roughness made using a profilometer. A tensile strength level of approximately 185,000 psi for all material was obtained by quenching and

tempering. Three lots of plate bending fatigue specimens were shot peened with cut and pre-rounded steel wire shot. A CW-28 shot size with a Rockwell C hardness of 46 was blasted onto each of the four surfaces of the plates for approximately 2 minutes.

For control purposes, bending fatigue specimens from Heat No. 4 were cast oversize and machined. Specimens to be machined on cope and drag surfaces only and those to be completely machined were cast as one-half inch and five-eighths inch plates respectively. All plates were ground on a rotary surface grinder using a selective grinding procedure to assure equal removal of stock from opposite surfaces and minimize metal damage. Following machining, the specimens were subjected to tensile, fatigue and hardness tests utilizing standard procedures. The fatigue testing was conducted on two types of fatigue machines. R. R. Moore specimens were tested in four point reversed bending on standard R. R. Moore rotating beam machines operating at 10,000 cycles per minute. The bending specimens were tested on a constant load amplitude Sonnatag SF-1-U fatigue machine operating at 1800 cycles per minute. All plate bending specimens were tested in reverse bending under four point loading. The dimensions of the unmachined bending specimens were measured and machine loading correspondingly adjusted to account for dimensional inaccuracies of the cast plates. All specimens were considered to have failed when completely fractured. The plate bending fatigue tests were carried out at various stress levels to obtain curves of stress versus cycles to failure. The number of specimens used for a S-N curve ranges from fifteen to twenty. R. R. Moore specimens were also tested at different stress levels and six specimens were used per curve. The endurance limit for all specimens was based on ten million cycles.

RESULTS AND DISCUSSION

The detailed results and a discussion of these results are presented in the three interim technical reports that have been submitted on this contract. These reports are concerned with the thermal and mechanical behavior of molding materials and steel castings. They include a study of the dimensional stability of the molding materials and the effect of the molding materials on the surface roughness and fatigue behavior of the castings. The reports are dated September, 1964; November, 1965; and May, 1967. In addition to the interim technical reports submitted, two publications in the technical literature have resulted from this contract. These are the following:

Wallace, J. F. and Bates, C. E., "An Investigation of Thermal and Mechanical Stability of Mold Materials for Steel Castings," Modern Castings, May, 1966, p. 216, also Trans. AFS Vol. 74, p. 174.

Wallace, J. F. and Naro, R. L., "Effect of Mold Washes on Casting Surface and Casting Fatigue Properties of Steel" Trans. AFS, Vol 75.

The first paper was granted the Award of the Sand Division of the American Foundrymen's Society for 1966 as an outstanding contribution to the advancement of the foundry industry.

GENERAL SUMMARY

This work is summarized by presenting the abstracts from each of the interim technical reports submitted on this material.

A. Report of September, 1964

Test apparatus and technique were developed to measure the tensile strength of molding materials at elevated temperatures. The measurements of tensile strength obtained from this equipment permits a qualitative evaluation of the mechanical stability of the mold as molten steel enters and solidifies in the mold. The mold stability obtained with various refractory aggregate-binder combinations is a significant factor in controlling dimensional tolerances in the steel casting.

Several rammed mold materials consisting of various combinations of refractory aggregates and binders were investigated for use in producing high quality steel castings. Aggregates of mullite, molochite, silica sand, fused silica, calcined kyanite and calcined alumina were bonded with western bentonite and sodium silicate. Close dimensional control of the castings was obtained with fused silica, calcined alumina and silica sand bonded with sodium silicate and green, western bentonite bonded mullite. Better casting surfaces were obtained with the fused silica aggregate. A modified sodium silicate binder utilizing silicon metal fines to promote setting was investigated. The bond developed was stronger in tension and compression at both room and high temperatures than that produced by western bentonite or by gassing identical sodium silicate bonded aggregates. This sodium silicate-silicon fines binder combined with either fused silica or silica sand refractories provided a mold for casting steel to close dimensions with a good cast surface.

B. Report of November, 1965

A test apparatus was developed to measure the tensile strength of molding materials at elevated temperatures. The measurements of tensile strength obtained from this equipment permits a qualitative evaluation of the ability of a mold to maintain casting dimensions.

Several rammed mold materials consisting of various combinations of refractory aggregates and binders were investigated for use in producing high quality steel castings. The aggregates selected for study included mullite, zircon, silica sand, fused silica, olivine, and calcined alumina. These were bonded with western bentonite and sodium silicate. Close dimensional control was obtained with all aggregates bonded with sodium silicate and with the zircon and mullite aggregates bonded with western bentonite. The casting surfaces obtained

with the fused silica and zircon were generally superior to those produced in other aggregates.

A technique was developed for measuring and recording mold wall deformation continuously during pouring and solidification of steel castings. Using this technique, mold deformations were measured at various distances from the mold-metal interface in molds rammed to different densities when western bentonite and sodium silicate binders were utilized. Mold deformation was found to be limited to a thin layer of the mold adjacent to the casting in all cases. This result indicates the importance of this thin layer in determining the dimensions of the final casting.

C. Report of May, 1967

This research investigated the effect of mold coatings and refractories on the surface quality of cast steel. The influence of surface roughness in reversed bending fatigue was also examined using as-cast specimens of AISI 4330 steel produced in green sand molds coated with hexachlorobenzene, aluminum powder, sodium fluoroaluminate, and a proprietary mold wash. Plate bending specimens were also produced in uncoated silica, chromite and zircon sand molds and subsequently tested. All specimens were heat treated to approximately 185,000 psi tensile strength levels as determined from tensile specimens from keel block legs. Control and comparison tests were made with R. R. Moore, tensile, and machined plate specimens.

Test specimens made in both hexachlorobenzene coated silica sand molds and zircon sand produced equivalent results in improving the surface finish of experimental test castings. Bending fatigue test results showed that hexachlorobenzene coated and uncoated zircon provided the greatest overall improvement in fatigue life and endurance limit. Completely machined bending fatigue specimens result in only slight improvements in fatigue compared to sand blasted hexachlorobenzene and zircon specimens with the original cast surfaces. Shot peening these specimens also produced substantial gains in fatigue strength, compared to machined specimens. The fatigue failures were initiated at cope surfaces with greater frequency than drag surfaces.

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2. Dimensional Accuracy		2. Dimensional Accuracy
3. Cast Surface Finish		3. Cast Surface Finish
4. Mechanical Properties		4. Mechanical Properties
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